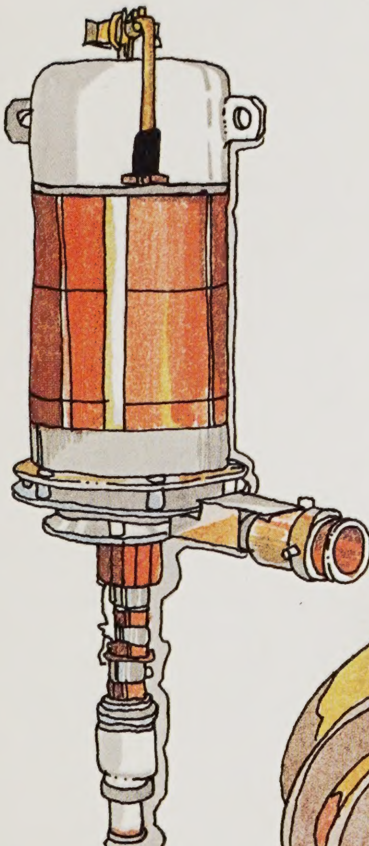

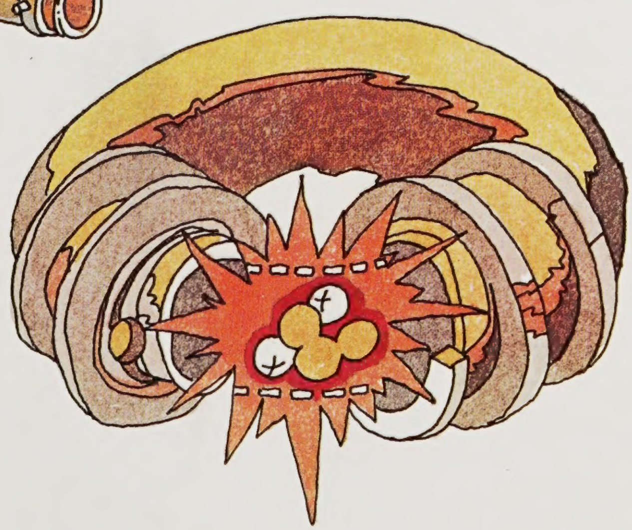

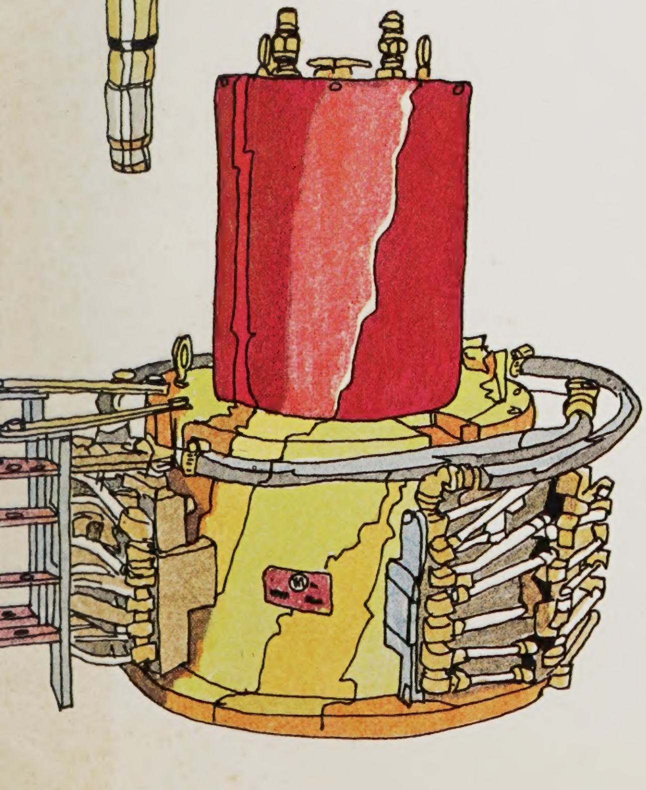

Introduction to Gyrotrons

varian

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

The gyrotron is a microwave vacuum tube based on the interaction between an electron beam and microwave fields where coupling is achieved by the cyclotron resonance condition. This type of coupling allows the beam and microwave circuit dimensions to be large compared to a wavelength. Thus the power density problems encountered in conventional traveling wave tubes and klystrons at millimeter wavelengths are avoided in the gyrotron. Figure 1 illustrates the power handling capability of the gyrotron compared to conventional devices.

The name ''gyrotron'' has been used to describe microwave oscillators based on the interaction of electrons orbiting in a dc magnetic field under the conditions of cyclotron resonance where the magnitude of the dc magnetic field and the microwave frequency are specifically related. These devices were single-cavity oscillators where the entire interaction took place in a single microwave cavity. It should be recognized that the same basic interaction can be used with different variations, such as amplifiers, using several resonant cavities or traveling wave circuits. These variations can be called gyroklystrons, gyro-TWTs, etc. Also the term ''cyclotron resonance maser'' has been frequently used in the literature to describe the same basic interaction, which emphasizes that the interaction can be described using either classical or quantum mechanics.

One motivation for the current work has been to develop microwave power sources for heating plasmas for controlled fusion. However, once developed, these devices can clearly have other applications such as high resolution millimeter wave radar or high directivity communications.

Varian has been working actively on gyro-devices since 1975 and has achieved significant results. In addition to developing analyses and computer codes describing beam characteristics and interaction processes for the various devices: oscillators, gyroklystron amplifiers and gyro-TWT amplifiers have been built and tested. A further decription of these devices and the results are given in the following sections.

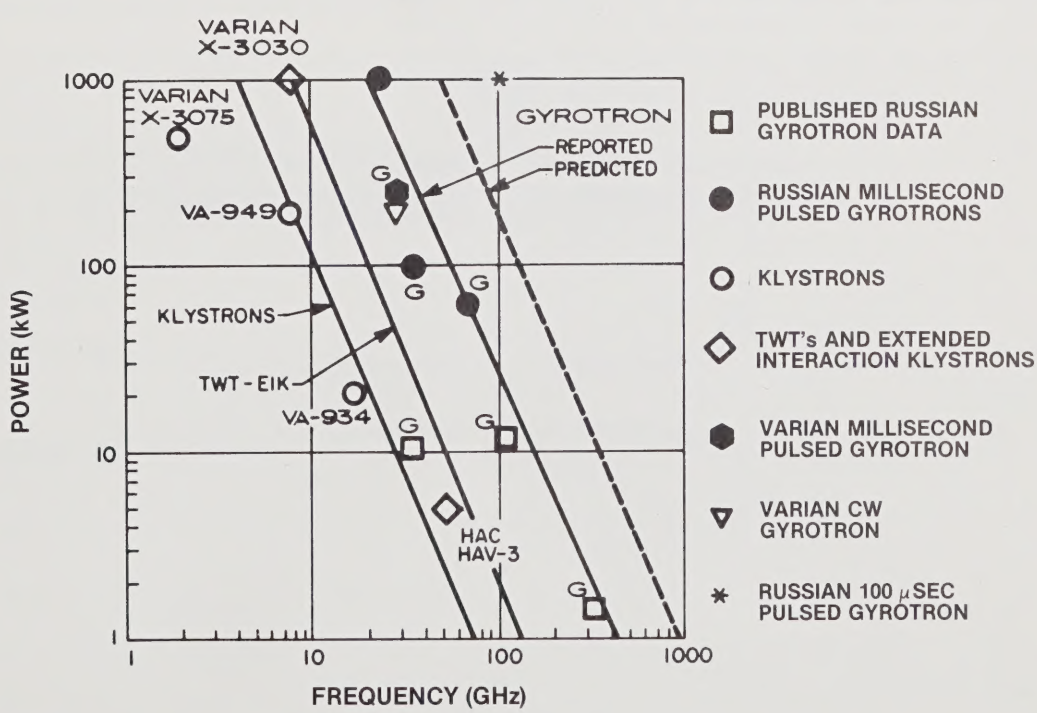

Figure 1. Long Pulse or CW Microwave Sources

II. BASIC CHARACTERISTICS

Gyro-devices require an electron beam where most of the electron energy is transverse to the axis of the tube; unlike linear beam tubes such as klystrons and TWTs where energy parallel to the axis is all that can be used. This has necessitated the development of a series of new electron guns for these devices. These are called "magnetron injection guns" because of the similarity to the electron trajectory in a magnetron. The beam of electrons with their cyclonic motion is injected into the interaction region where the energy exchange between the electrons and the rf wave takes place. A schematic diagram of this is shown in Figure 2 along with a cold test section for a gyroklystron amplifier.

An important characteristic of the gyrotron is that it requires the application of a dc magnetic field which is specifically related to the operating frequency by the cyclotron resonance condition. This relationship is given by the equation

$$\omega = n\omega_c \quad (1)$$

where ω is the operating frequency, n is an integer and ω_c is the cyclotron frequency or angular velocity of the electron given by

$$\omega_c = \frac{eB}{\gamma m_o} \quad (2)$$

B is the dc magnetic field, e is the electron charge, m_o is the rest mass, and γ is the relativistic mass factor. Effective interaction occurs only for magnetic fields where n is near integer values. For most microwave field shapes, such as encountered in conventional waveguides and resonators, the fundamental resonance condition with n = 1 has the strongest interaction. With certain special microwave field shapes useful interaction can take place with larger integer values of n. These harmonic interactions have the advantage that the magnitude of the dc magnetic field for a given frequency can be reduced by 1/n. The salient gyrodevice characterisitcs and their implications are shown in Table 1.

For the fundamental resonance condition, a frequency of 28 GHz requires a 10 kG magnetic field. For higher frequencies, proportionally higher fields are needed. This has led to the use of superconducting magnets in many higher frequency experiments. Operation at the second harmonic of the cyclotron resonance has been accomplished, which allows a reduction in magnetic field by a factor of two.

In the gyrotron, bunching of the electron beam occurs as a result of a relativistic effect. This can be seen from Equation 2 where a change in electron kinetic energy results in a change in angular velocity of the electron. In the gyrotron single-cavity oscillator, microwave electric fields in the early part of the cavity apply an angular velocity modulation to the electrons. As the electrons drift

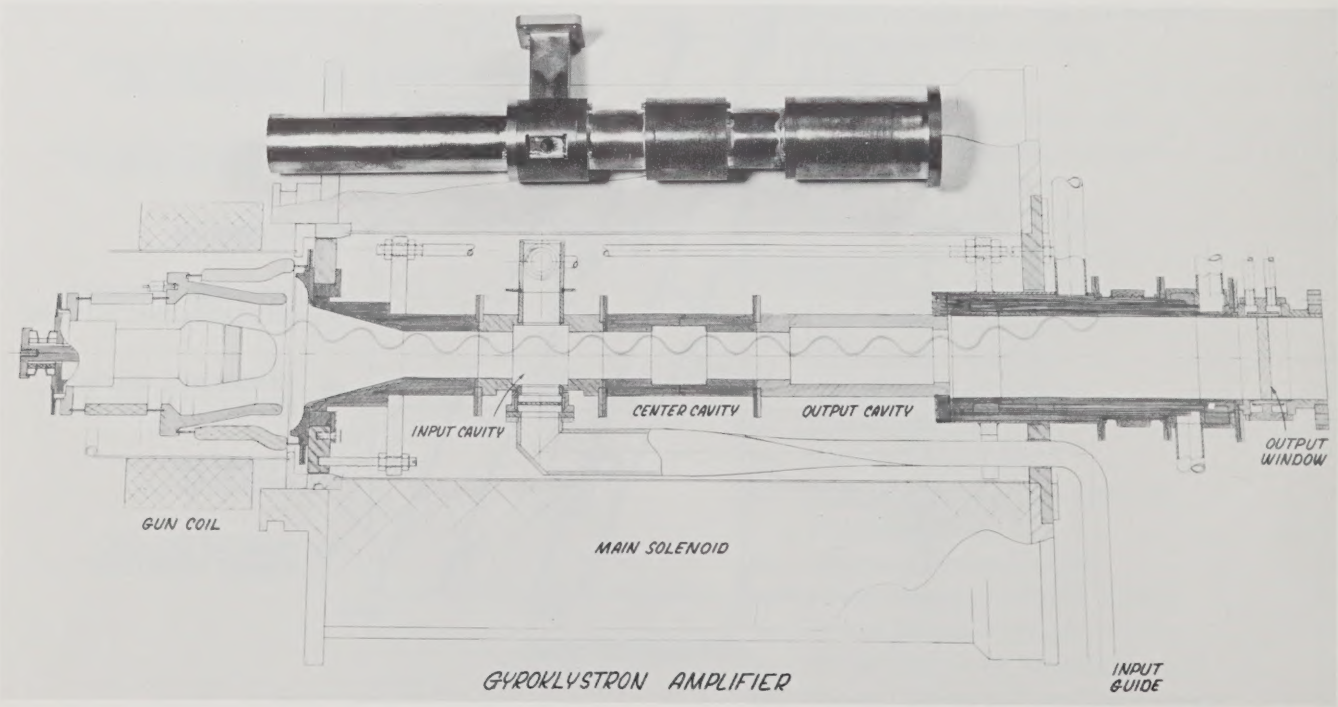

Figure 2.

TABLE 1
Gyro-Devices

Characteristics	*Implications*
1. Large area for beam and microwave circuit 100 times area in klystron or conventional TWT	100 times power output of conventional tubes
2. Applied magnetic field proportional to frequency $B(kG) \sim 0.35\ f(GHz) \times \frac{\gamma}{n}$ γ = Relativistic mass factor n = harmonic number	Superconducting magnets for 60 GHz or higher

further through the cavity, angular bunching takes place as a result of the angular velocity modulation. This angular bunching is shown schematically in Figures 3 and 4. Toward the end of the cavity the phase between electron bunches and the microwave electric fields is adjusted so that the electrons give up kinetic energy. When the energy given up by the electrons exceeds the cavity losses, an oscillation results and output power is available.

Although a relativistic effect is involved in the interaction, efficient gyrotrons have been built using beam voltages as low as 18 kV. An optimum voltage range is probably 50 to 100 kV.

The frequency of the single-cavity gyrotron oscillator is influenced by both the cavity resonance and the value of the dc magnetic field. In general, the output frequency is approximately linearly related to the dc magnetic field over the half power bandwidth of the cavity. Practical cavity Qs are in the range of 500 to 5000. Higher frequency stability requires tighter control on magnetic field.

In the gyroklystron, an input cavity is used to modulate the beam and subsequent cavities are used for further amplification or energy removal. An experimental device of this type will be discussed in a later section. In the gyroklystron, instantaneous bandwidths of 1% are practical.

Another variation which has a larger bandwidth is the gyro-TWT. In this case a propagating waveguide is used for continuous interaction with the beam. An instantaneous bandwidth of 5 to 10% is achievable and magnetic tuning should double the available bandwidth. Gyro TWT power gain of 20 to 30 dB and an efficiency of 15 to 25% have been achieved in early Varian experiments.

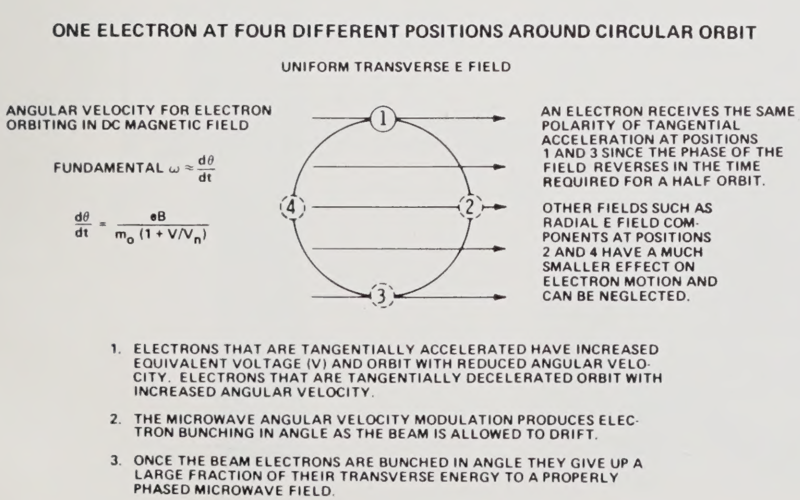

Figure 3. Basic Gyrotron Interaction

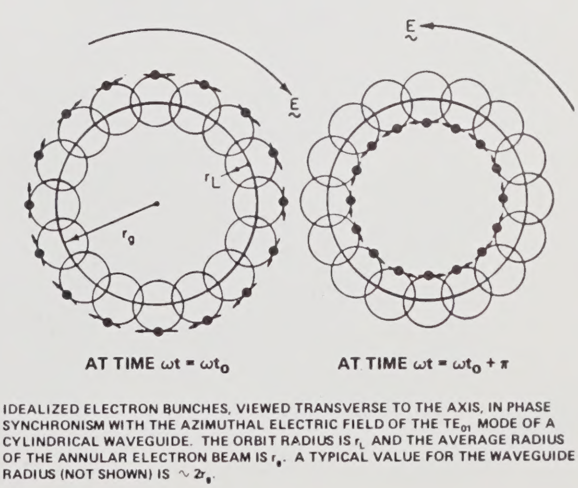

Figure 4. Idealized Electron Bunches

III. PROGRAMS AND RESULTS

- **Gyrotron Oscillator**

After a thorough investigation in 1975 Varian determined that the gyrotron concept was the most effective way of obtaining hundreds of kilowatts of CW power at millimeter frequencies. Gyrotron oscillators producing hundreds of kilowatts of peak power had been reported by the Soviets and the need for high CW and long pulse power at high frequencies for plasma heating in U.S. fusion energy experiments resulted in a program at Varian for the developmet of a 200 kilowatt CW gyrotron at 28 GHz.

The initial investigations were carried out in a pulsed device and a cross section view of that tube with its attendant focusing magnet is shown in Figure 5. In this device the electrons are emitted from a narrow annular band on the inner element of the electron gun. Their trajectories are controlled by the surrounding anode, which is referred to as the "gun anode" to differentiate it from the anode which is part of the tube body, and the magnetic field created by the gun coil. The beam is compressed by the main magnet field and passes through the interaction cavity. The beam continues into the collector region and is dissipated on the water cooled walls of the collector. From the interaction cavity the rf follows the taper to the 2.5 inch cylinder, which is just beyond the collector, and is taken out through a vacuum window. The development of this device was very successful and they are now being operated by experimenters for plasma heating. The typical peak power output is 200 kilowatts at 28 GHz and pulse lengths out to 40 milliseconds have been demonstrated. The typical operating parameters are shown in Table 2, and the power output performance versus beam current is shown in Figure 6. It should be noted that the measured power output agrees exceptionally well with that calculated using Varian's theoretical analysis.

Table 2
28 GHz Gyrotron VGA-8050A

Beam Voltage	80 kV
Beam Current	8 A
Magnet Field	11 kG

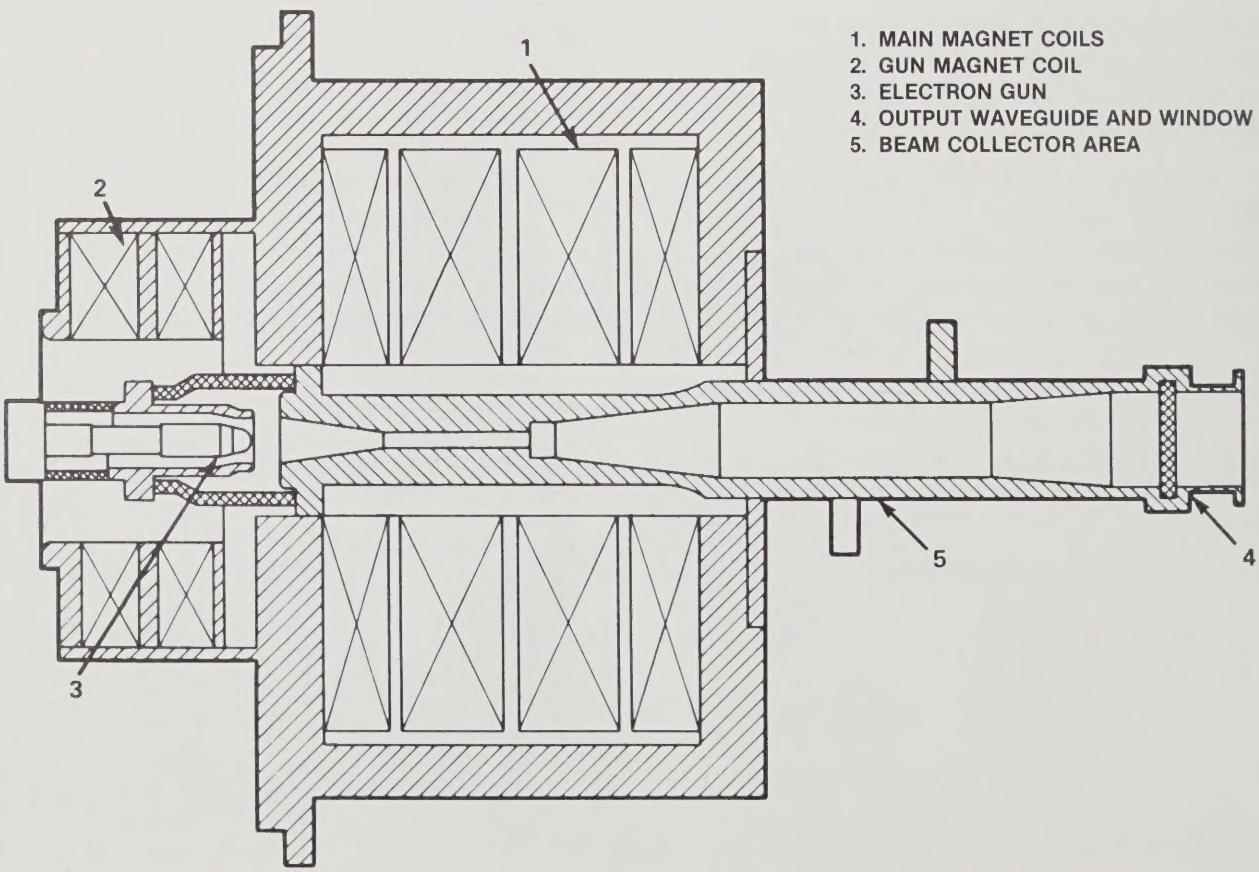

Figure 5. Gyrotron in Focus Magnet

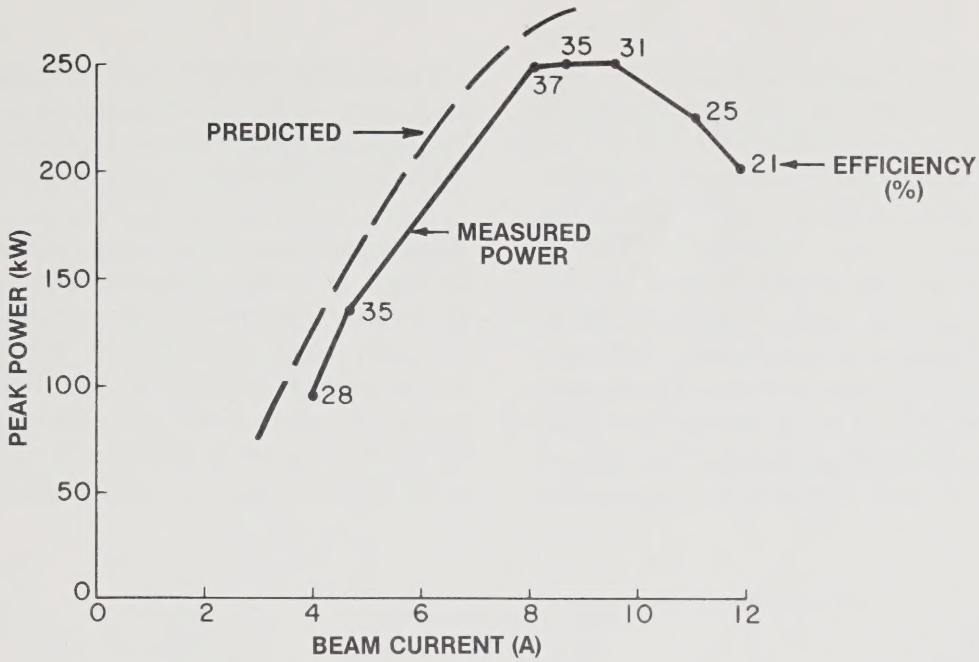

Figure 6. Peak Output and Efficiency for Pulsed Oscillator

The required dc magnetic field was obtained using a room-temperature magnet wound with hollow core, water cooled copper conductors. The tube alone and the tube in the focus magnet are shown in Figures 7 and 8.

Figure 7. The VGA-8050A

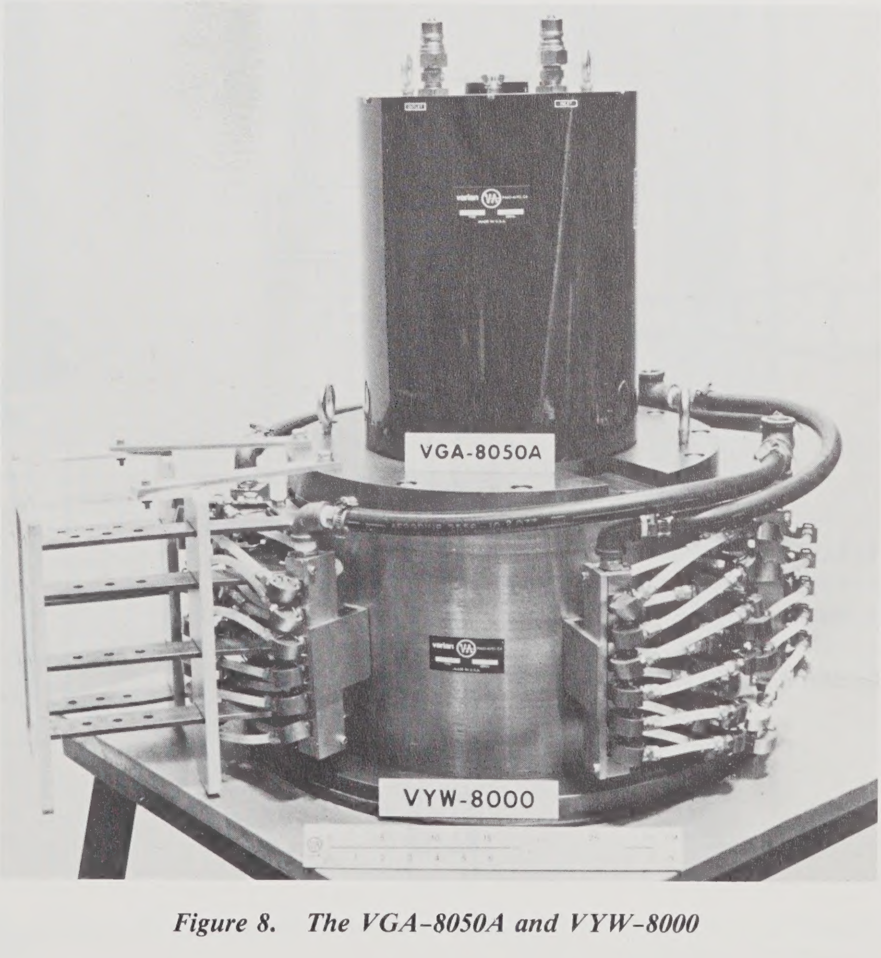

Figure 8. The VGA-8050A and VYW-8000

The goal of the program was to develop a device which was capable of 200 kW CW operation at 28 GHz and two mechanical formats were used in CW tubes. The first was a straightforward high-power approach to the collector design with a more exotic approach to the rf output transducer. This is shown schematically in Figure 9 and in the photograph in Figure 10. In this case the rf output is brought out of the interaction region in 1.25 inch circular waveguide by means of three miter bends. The first miter at the end of the cavity has a hole large enough for the beam to pass through and at this point the rf and the electron beam are separated. The beam is then dissipated in the heavily cooled collector while the rf is brought out through the three miter bends and a taper to the 2.5 inch output window.

The second mechanical format utilizes the straight-through rf design demonstrated on the pulsed gyrotrons. This makes the collector design considerably more cumbersome but eliminates the mode mixing created by the miter bends. A schematic of this is shown in Figure 11 and Figure 12 is a photograph of the tube. In this design the rf guide tapers from the cavity diameter up to a

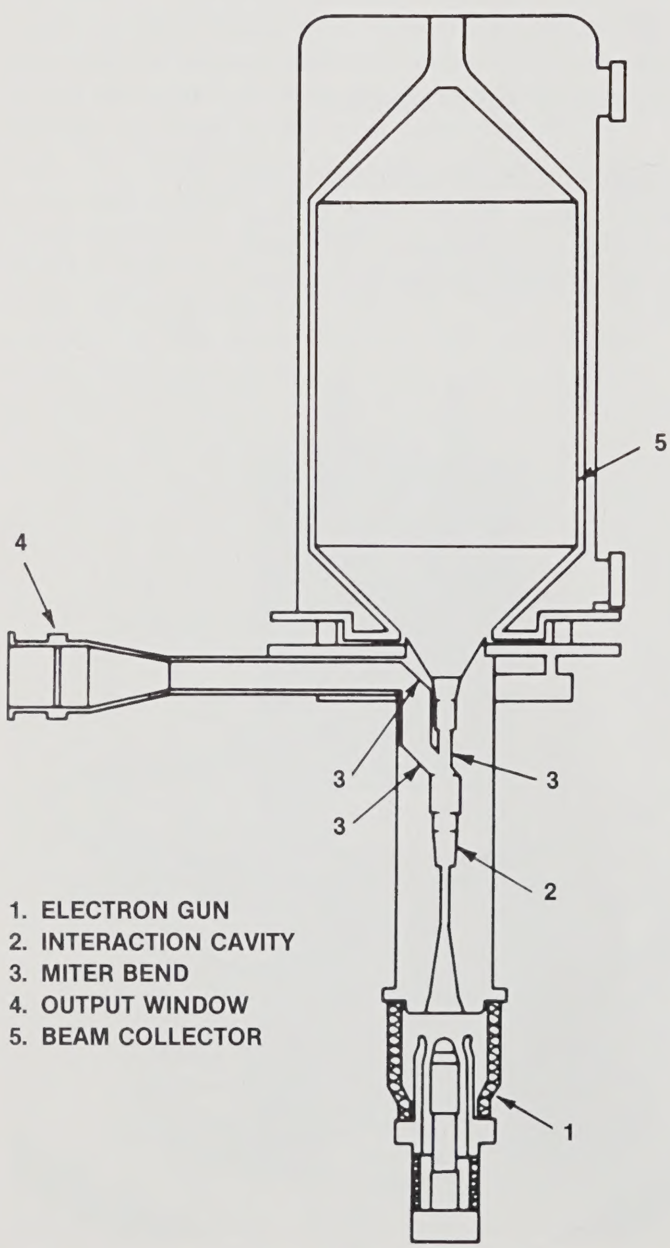

Figure 9. CW Gyrotron With Miter Output Guide

Figure 10. Gyrotron VA-800A, With Triple Miter Bend RF Output

5-inch diameter in the heavily cooled region of the collector where the beam is dissipated. The guide then tapers back to a 2.5-inch diameter at the output window. In both designs the same electron gun and focus magnet are used as on the pulsed tube. Only the rf extraction and beam dissipation systems are modified.

The results for operation of tubes in each mechanical format are shown in Table 3.

Table 3

Triple Miter Bend		Axisymmetric
Frequency	28	28 GHz
Peak Pulsed Power Output	175	213 kw
CW Power Output	105	212
Efficiency	17	40%

It should be noted that in the axisymmetric tube efficiencies as high as 47% were attained at 150 kW power output. Work is continuing in the area of product refinement and additional tubes in both formats are being built.

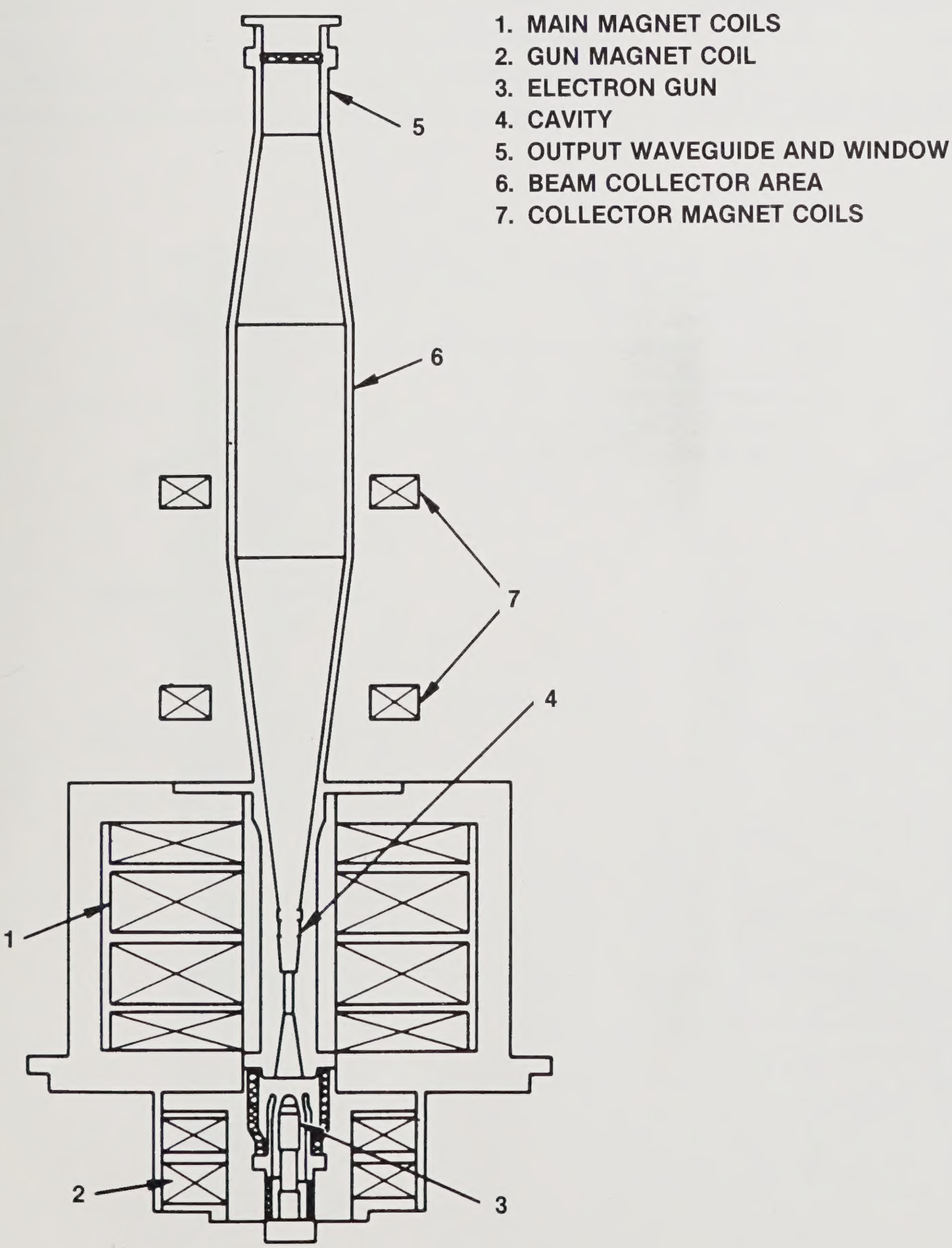

Figure 11. CW Gyrotron With an Axisymmetric RF Output

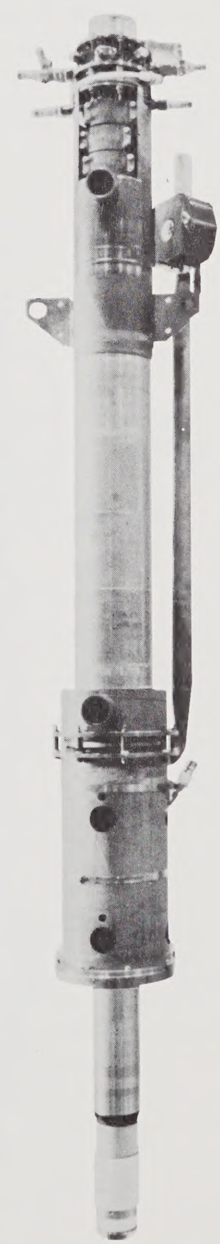

Figure 12. Gyrotron VGA-8000B, With Axisymmetric RF Output

• **Gyroklystron Amplifier**

Utilizing the cyclotron resonance interaction described earlier, a resonant cavity amplifier has been built employing two cavities. Figure 13 is a schematic drawing of that device. It will be noted that there are many similarities to the pulsed oscillator. In this device the same electron gun and collector are used as well as the same electromagnet. Additional experiments were performed at 10 GHz on a program investigating second harmonic interaction; however, the results were not encouraging and that effort was dropped. The results achieved at 28 GHz are shown in Table 4. The variations in power output and gain are a result of optimizing conditions to maximize one or the other. As in a klystron some efficiency is sacrificed to maximize the gain.

This tube is shown in Figure 14. It is believed that the low efficiency is caused by too long a drift space between the input and the output cavity. At this time the tube is being rebuilt as a three-cavity device and will be tested at the earliest opportunity.

Table 4
Measured Results

Power Output	25 - 65 kw Peak
Power Gain	40 - 30 dB
Frequency	28 GHz
Cyclotron Harmonic	Fundamental
Magnetic Field	11 kG
Beam Voltage	80 kV
Beam Current	8 A
Efficiency	10 %
Bandwidth	0.2%
Duty Factor	5%

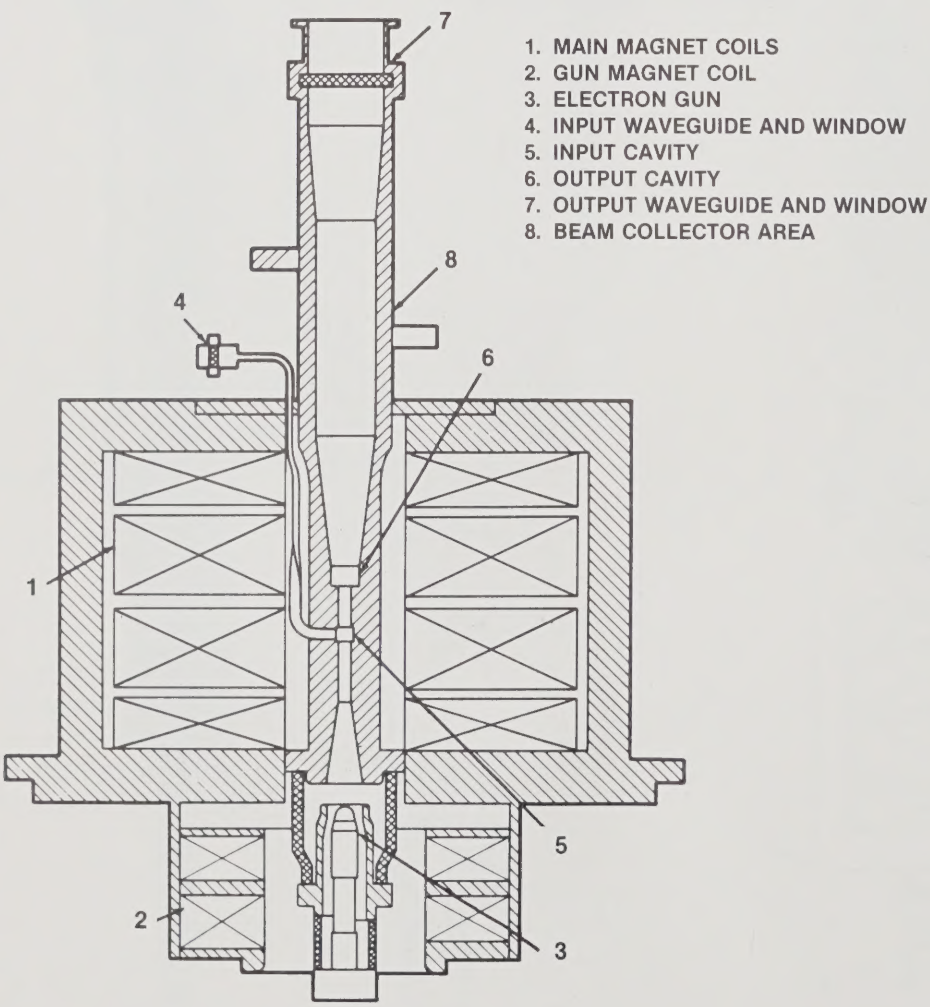

Figure 13. Layout Drawing of a Pulsed Gyroklystron Amplifier

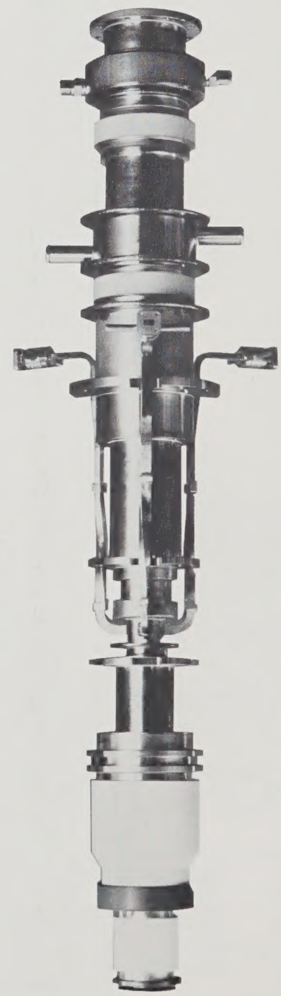

Figure 14. Gyroklystron Amplifier

• Gyro-TWT

The work at 28 GHz has been part of a program to develop devices for use in heating plasmas for magnetic fusion energy experiments and bandwidth has not been a consideration. For applications such as radar and communications a coherent amplifier is preferred and, in addition, some bandwidth is desirable. In pursuit of these applications Varian started work on a device, again utilizing the cyclotron resonance interaction phenomonon but with a non-resonant structure, as used in a traveling wave tube. In this case the interaction structure is a circular waveguide excited in the circular TE_{11}^{o} mode. A schematic drawing of this device is shown in Figure 15. The electron gun and collector are similar to the 28 GHz pulsed gyrotrons. The interaction waveguide is excited by two rectangular waveguide to circular waveguide transitions at 90° to each other in order to match into the two orthogonal TE_{11}^{o} modes that can exist in the circular waveguide. As with other pulsed tubes the rf output is extracted through a window at the end of the collector. Figure 16 shows the gyro-TWT for which data is tabulated in Table 5.

Table 5
Description of Experimental Gyro-TWT

Frequency	5 GHz scalable to 95 GHz
Mode	TE_{11}^{o} circular polarized
Power	120 kW Peak
Gain	26 dB
Efficiency	26% maximum observed
Bandwidth	7.25% 3 dB saturated power
Voltage	65 kV
Current	7.0A

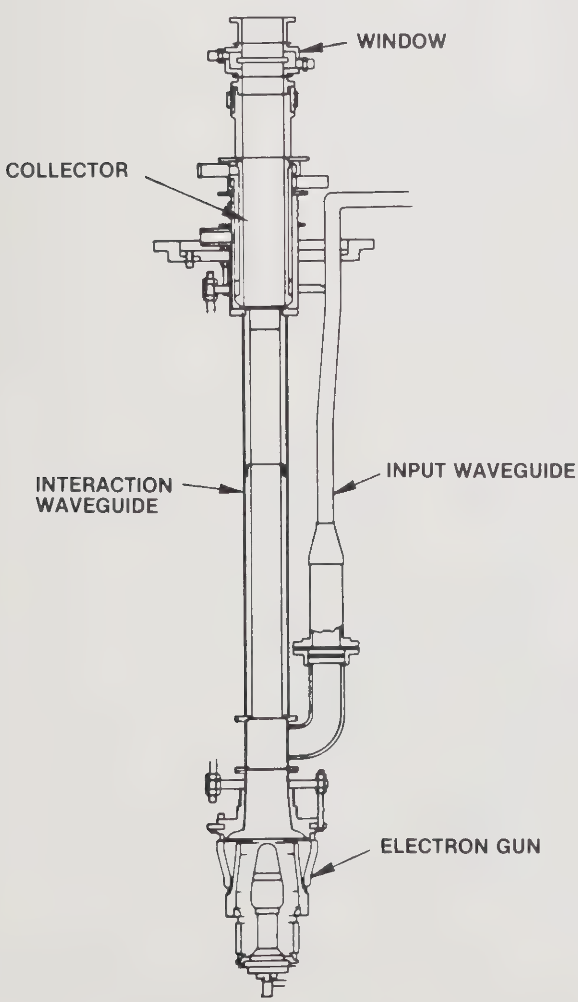

Figure 15. Section of Gyro-TWT

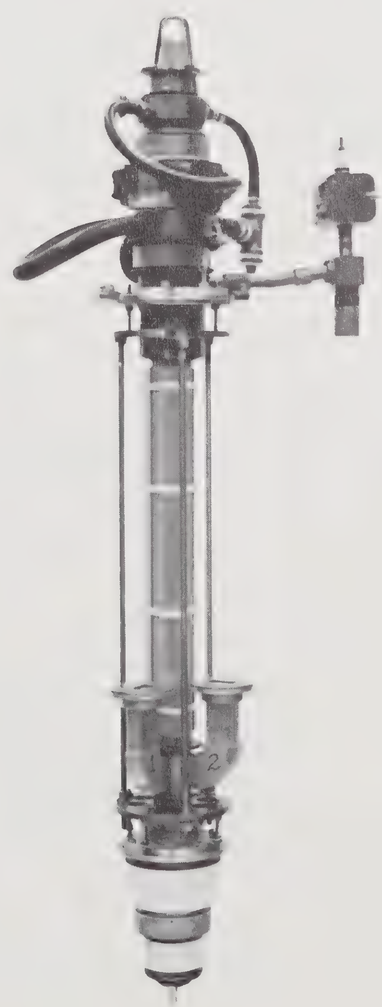

Figure 16. Gyro–TWT Amplifier

As noted, this work was done at 5 GHz. Peak power output versus frequency at 455 kW beam power is shown in Figure 17. In Figure 18, peak power output versus frequency at 160 kW beam power is shown. The data displayed in Figure 18 was taken to demonstrate the dual mode capability of the gyro-TWT, i.e., the gyro-TWT can be operated CW in the low power mode and then in the high power mode by increasing beam voltage and current, operation with negligible loss in bandwidth.

The next phase of this work will include scaling the design to 95 GHz, and building a gyro-TWT at that frequency with 50 kw peak power output, 10% duty cycle and 40 dB gain.

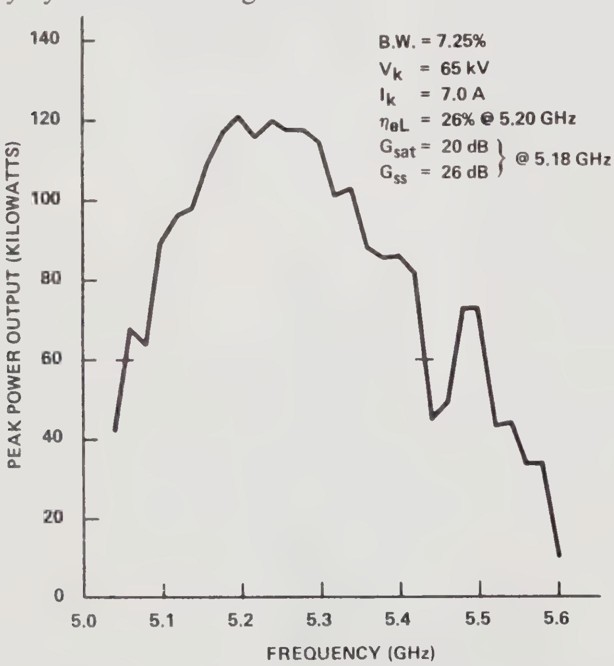

Figure 17. Peak Power Output vs. Frequency

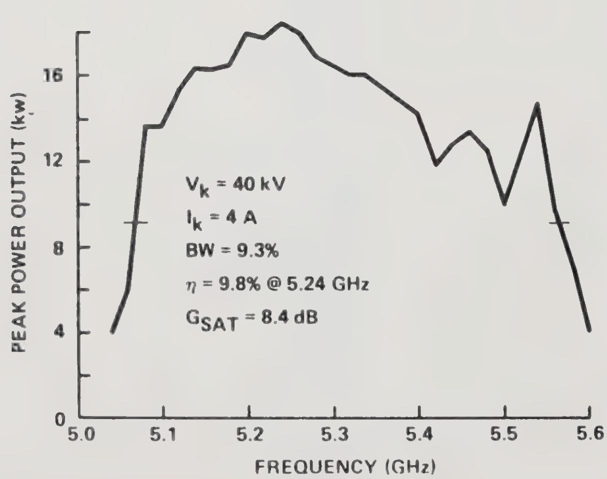

Figure 18. Power Output in the Low Power Mode

IV. GYROTRON OPERATION

The requirements for operation of the gyrotron, whether oscillator or amplifier, are similar to those for any linear beam tube such as a high-power klystron or TWT. However, differences exist and as the designs evolve and become more sophisticated some changes in method of operation can be expected. Shown in Table 6 are the operating parameters for a typical 200 kilowatt pulsed oscillator.

Table 6
Operating Parameters

Frequency	28 GHz
Beam Voltage	80 kV
Beam Current	8 a
Gun Anode Voltage	25 kV
Magnet Coil Current	
Main Coil #1	480 A
Main Coil #2	472 A
Main Coil #3	480 A
Main Coil #4	480 A
Gun Coil #1	10.2 A
Gun Coil #2	10.0 A
Heater Voltage	8.1 V
Heater Current	4.6 A
Body and Collector Water Flow	15 gpm
Normal Tube Pressure (with Heater Voltage)	$<10^{-8}$ Torr
Maximum Duty Factor	5%
Rated Pulse Length	20 ms

The beam voltage and mod-anode voltage are referenced to the cathode with the body of the tube operating at ground. The voltages for the main magnet coils are approximately 26 volts each depending upon the coil temperature. The magnet requires a minimum water cooling flow of 15 gpm. The voltage for the gun coils is 33 volts each. The electron gun and gun coils are operated in an oil tank with a small pump being required to circulate the oil up into the electron gun. All gun electrical connections and the oil cooling connections for the gun are accomplished by plugging the tube into a socket.

Power output is affected by changes in the values of several parameters; typical examples are shown in Figures 19 through 22. The present gyrotrons

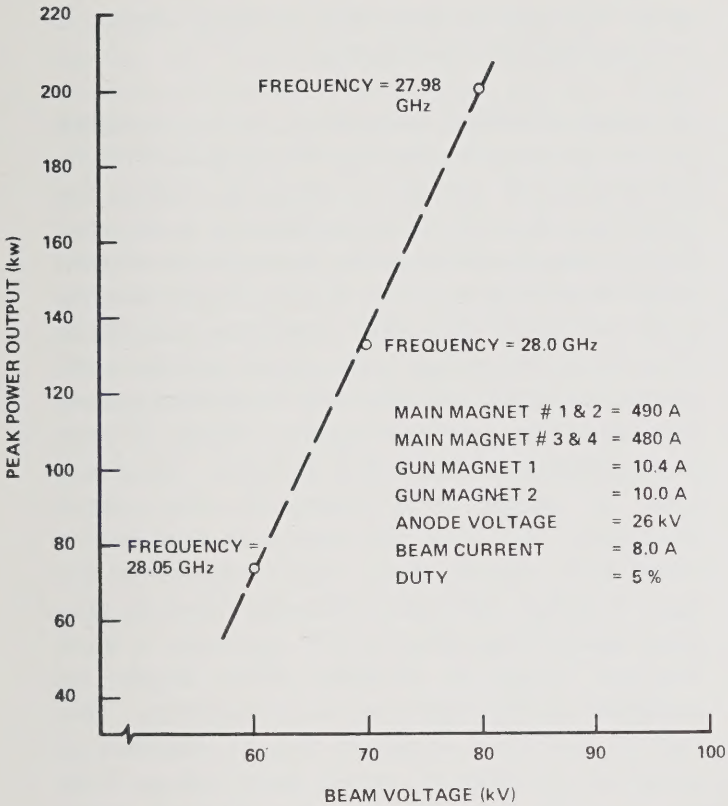

Figure 19. Power Ouput vs Beam Voltage

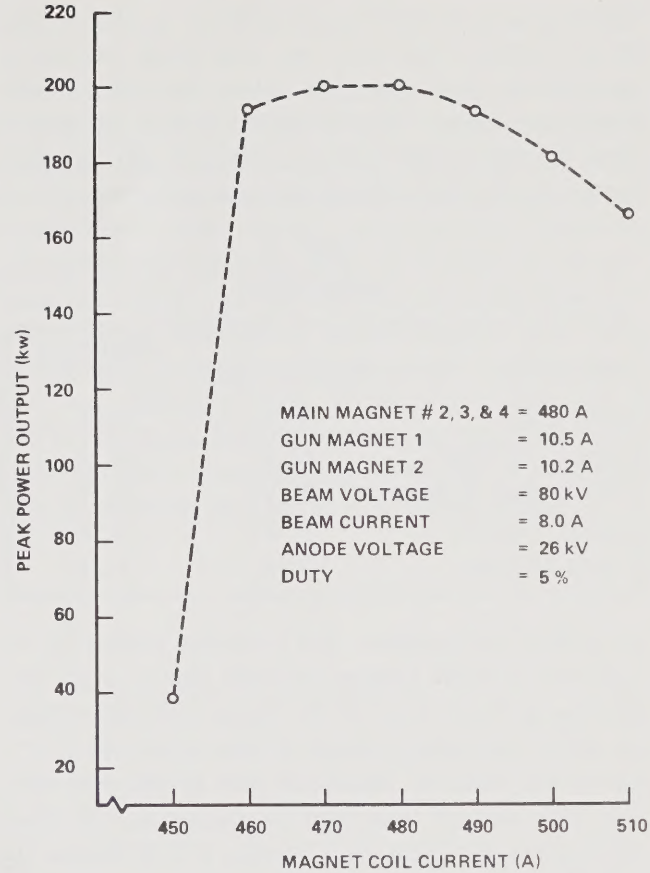

Figure 21. Power Output vs Main Magnet Current (One Section Only)

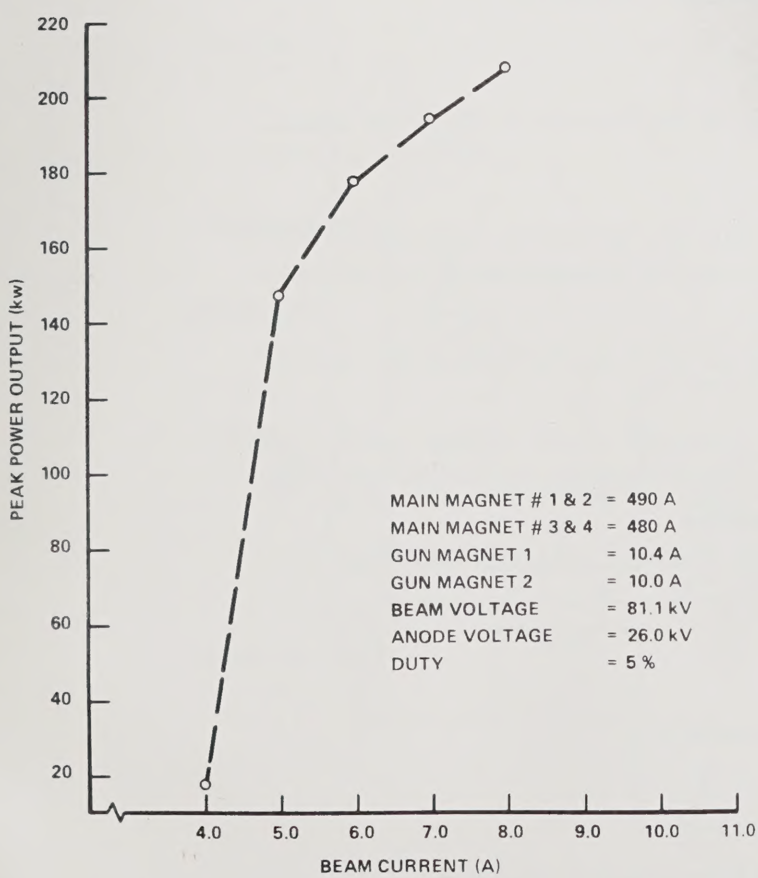

Figure 20. Power Output vs Beam Current

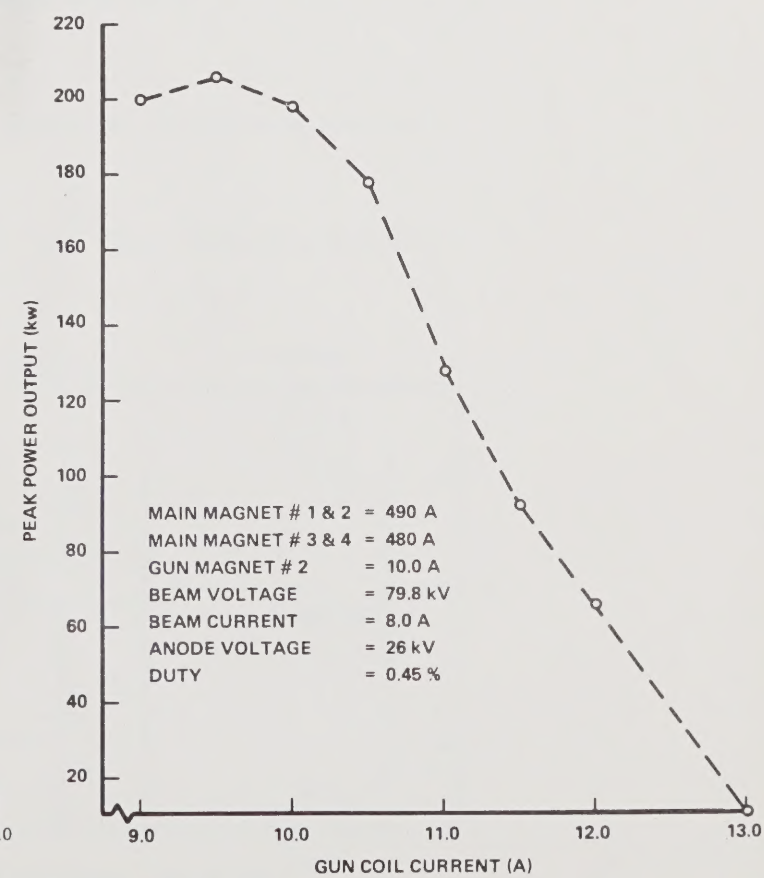

Figure 22. Power Output vs Gun Coil Current

utilize a temperature limited cathode to control the beam current. That is to say that beam current is controlled by changing the cathode emission/temperature. This is accomplished by variations in the heater voltage. Table 7 gives typical sensitivities to these critical parameters.

Table 7
Sensitivities

Parameter	*Typical Value*	*Sensitivity (dB %)*
Gun Coil	10 A	0.11
Heater Voltage	12 V	0.32
Gun Anode Voltage	25 kV	0.39
Beam Voltage	80 kV	0.54
Main Magnet	500 A	1.21

In pulsing the gyrotron, the preferred method is to hold the cathode voltage constant and to pulse the gun anode from 1 to 1.5 kV below cathode voltage up to the operating voltage of approximately 25 kV above the cathode. Since the gun anode intercepts very little current, less than 20 milliamps, this does not require switching high energy. If it is desired to cathode pulse the tube then some provision must be made to keep the gun anode at a voltage less than the proportional cathode operating voltage during the rise and fall of the cathode voltage pulse. This can be done with a voltage divider if proper precautions are taken.

A typical simplified schematic is shown in Figure 23 for operating a gyrotron. The collector will be off ground by enough to allow monitoring the body current. Some protection must be provided to limit the energy which can be discharged in the tube in the event of an arc. This is normally provided by a crowbar which fires within 5 microseconds in the event of an arc or high body current and limits the energy discharged into the tube. Additional protection must be provided against failure of the magnetic field, coolant flow failure in either the tube or magnet and arcing in the output waveguide. This latter will require an arc detector which looks directly at the output window. In the case of pulsed tubes some protection must be provided against long pulses or CW operation. A small Vac-Ion® pump is provided which should be energized during operation as a minimum. This may be monitored visually or may be connected to protection circuitry to remove beam voltage from the tube in case of excessive Vac-Ion pump pressure.

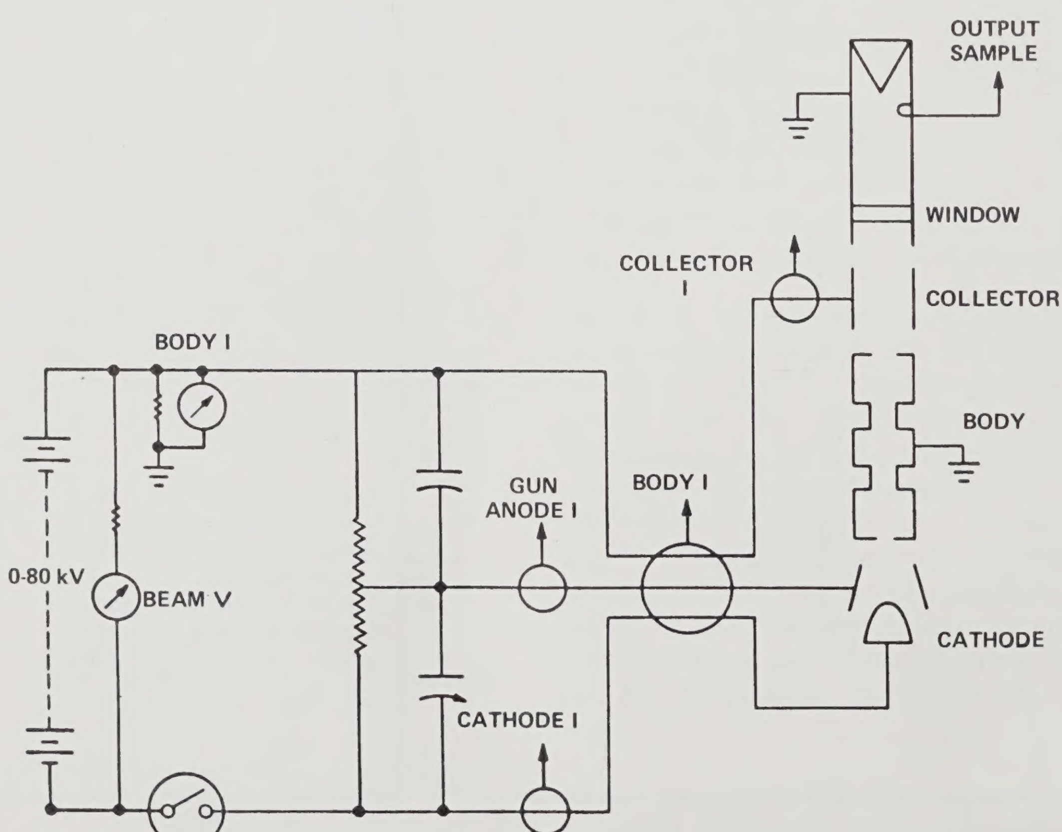

Figure 23. Operating Connections for Gyrotron

V. FUTURE PROJECTS

Gyrotrons are only now becoming products capable of "everyday service", as opposed to scientific curiosities. Pulsed tubes are now being delivered by Varian at 28 GHz, 200 kW power output. CW oscillators have been delivered for service on the Elmo Bumpy Torus at Oak Ridge National Laboratory and will soon be generally available. Current development effort is being applied to 60 GHz oscillators with the anticipation that 90 GHz and higher frequencies will follow in a few years. These devices are intended as 200 kW devices for both pulsed and CW operation. The Soviets have reported results on a tube operating at 328 GHz so it is quite feasible in time, to expect high power devices in the hundreds of GHz region.

The principle thrust to date has been for plasma heating applications. However, as mentioned earlier, coherent amplifiers have been demonstrated and should generate more interest in the radar, communications and ECM communities. Further measurements are being made at Varian on the existing gyro-TWT to provide more information on noise, phase sensitivites, phase linearity and AM distortion. This information should be available soon and it is anticipated that within a few years gyro-TWTs will be available at higher frequencies (35 to 95 GHz) for systems applications up to 100 kw peak and tens of kilowatts average or CW power output.

ACKNOWLEDGEMENTS

Varian would like to acknowledge the support of the following agencies in sponsoring this work.

U.S. Department of Energy, through Oak Ridge National Laboratory, operated by Union Carbide Corporation.

Defense Advanced Research Projects Agency

U.S. Army, Ballistic Missile Defense
Advanced Technology Agency Center

U.S. Air Force, Rome Air Development Center.

Varian Electron Device Group Sales Office Locations

U.S. SALES OFFICES

Boston
83 Second Avenue
Burlington, Massachusetts
01803
TEL: (617) 272-8532

Chicago
205 W. Touhy Avenue
Park Ridge, Illinois 60068
TEL: (312) 825-6686

Clearwater
314 South Missouri
Suite 307
Clearwater, Florida 33516
TEL: (813) 446-8513

Dallas
13531 N. Central Expressway
Suite 2343
Dallas, Texas 75243
TEL: (214) 235-2385

Dayton
4134 Linden Avenue
Suite 101
Dayton, Ohio 45432
TEL: (513) 258-3930

Huntsville
500 Wynn Drive, N.W.
Suite 301-F
Huntsville, Alabama 35805
TEL: (205) 837-9225

Los Angeles
2901 Wilshire Blvd.,
Suite 205
Santa Monica, Calif. 90403
TEL: (213) 828-5588

New York (Metropolitan)
25 Commerce Drive
Cranford, New Jersey 07016
TEL: (201) 276-9050

Philadelphia
306 Fellowship Road
Mount Laurel, New Jersey
08054
TEL: (609) 235-6800

Phoenix
7345 E. Earll Dr.
Suite 30
Scottsdale, Arizona 85251
TEL: (602) 947-5461

San Francisco
375 Distel Circle
Suite C-4
Los Altos, California 94022
TEL: (415) 968-7630

Syracuse
6489 Ridings Road
Syracuse, New York 13206
TEL: (315) 437-2568

Warner Robins
United Finance Bldg.,
Suite #4
1600 Watson Blvd.
Warner Robins, GA 31093
TEL: (912) 922-2202

Washington D.C.
4701 Lydell Road
Cheverly, Maryland 20781
TEL: (301) 773-7010

INTERNATIONAL SALES OFFICES

Headquarters
Varian Export Corp.
611 Hansen Way
Palo Alto, CA 94303
TEL: (415) 493-4000

Australia
Varian Pty. Ltd.
679 Springvale Road
North Springvale, VICT. 3171
Australia
TEL: 560-7133

Benelux
Varian Benelux BV
Maassluisstraat 100
P.O. Box 9158
Amsterdam, Holland
TEL: (020) 15 94 10

NV Varian Benelux S A
Avenue Charles Quint 545
1080 Brussels, Belgium
TEL: 02/466-20-00

Canada
Varian Canada Inc.
45 River Drive
Georgetown, Ontario, Canada
L7G 2J4
TEL: (416) 457-4130

Varian Canada Inc.
1335 Carling Avenue
Ottawa, Ontario, Canada
K1Z 8N8
TEL: (613) 728-4643

France
Varian S.A.
Quartier de Courtaboeuf
Boite Postale No. 12
91401 Orsay
France
TEL: (6) 907 78 26

Germany
Varian GmbH
Allacher Strasse 230E
8 Munchen 50, West Germany
TEL: (089) 812 60 93

Italy
Varian SpA
Via Fratelli Varian
1-10040 Leini (Torino)
Italy
TEL: (011) 996 80 86

Japan
Marubun Corporation
8-1, Nihombashi
Odemmacho 2-Chome
Chuo-Ku, Tokyo, 103 Japan
TEL: (03) 662-8151

Scandinavia
Varian AB
Skytteholmsvagen 5
P.O. Box 1099
17122 Solna 1, Sweden
TEL: (08) 82 00 30

Switzerland
Varian A.G.
Grienbachstrasse 17
Postfach
6300 Zug, Switzerland
TEL: (042) 31 66 55

United Kingdom and Ireland
EMI-Varian Ltd.
248 Blyth Road
Hayes, Middlesex
UB3 1HR, England
TEL: 01-573-5555

varian

Pub. No. 4368 (Printed in U.S.A.) 680